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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND



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NANO-ENABLED TECHNOLOGIES FOR NAVAL AVIATION APPLICATIONS

by

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14. ABSTRACT Nano-technology is a rapidly emerging area of importance to Naval aviation. NAWCAD has identified nano-materials and meta-material technologies as an area of strategic importance. In order to better define the investment areas required, three nano-technology study groups were held in the areas of (i) energy and power, (ii) airframe structures, and (iii) electronics & meta-materials. Each study group consisted of a small number of technical experts drawn from academia, industry, DoD, and NAVAIR. The study group on energy and power concluded that power and thermal requirements for Directed Energy Weapons, Unmanned Air Vehicles, Electromagnetic Launch Systems and ground support systems will drive the need for nano-enabled technology. Nano-technologies of importance to naval aviation, to name a few, are: Carbon Nano Tubes for batteries, graphene for capacitors, nano-structured non-precious metal catalysts for Fuel Cells, and phase change materials for thermal management. This paper reports the results of the study group and links together nano-technology, applications, and required core capabilities.					
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SUMMARY

The Energy and Power Nanomet Study Group meeting was hosted by NAVAIR at NAVMAR in Lexington Park, MD. This was the first of a series of workshops designed to better understand the state-of-the-art in nano-enabling technologies, current challenges, potential benefits, potential application systems, and the required resources needed for investing in nano-material/nano-technology for Energy and Power systems. The primary goal of this study group is to determine what benefits NAVAIR could realize from investing in nano-technology across various platforms. The Energy and Power study group was divided into four subtopics: Batteries, Capacitors, Fuel Cells, and Thermal Management. Various members from Industry, Government and Academia were present and given an opportunity to present their views on nano-enabling technologies. The group discussed the nano-technology benefits, gap analysis, challenges, and benefits to the US Navy for each topic area as well as tried to identify performance attributes associated with each technology/material system for various applications. Break out session summaries of each topic area are listed in Table 1 (batteries), Table 2 (capacitors), Table 3 (fuel cell), and Table 4 (thermal management), respectively.

In general, it is clear that nano-materials and nano-technology will play a significant role in Energy and Power System applications ranging from high powered electronic devices to Unmanned Aerial Vehicles to Directed Energy Weapons and Electromagnetic Aircraft Launch System. The working group discussions resulted in the identification of significant benefits from nano-technology that the Navy could benefit if resources were provided to close the gap and realize the full nano-enabling technologies. Each of the four topical sessions is discussed in more detail in order to address the following questions:

1. What did we learn from the study groups?
2. What are the nano-enabling technologies?
3. What platform systems are most impacted?
4. What are the technical challenges/gaps that need to be filled?
5. Which of these gaps must/should the Navy address?
6. What is needed (people, facilities, funding) to properly address these gaps?
7. What are your thoughts as to how the command can best address these needs?
8. What immediate action can we take on our own to advance the Navy's needs in this area?

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INTRODUCTION

There has been significant world-wide investment in nano- and meta-materials over the last 15 years. There have been many projections of the tremendous economic benefit of these materials for a broad set of industrial applications. For instance, several reports have described a trillion-dollar impact of nano-materials for industrial applications. The vast majority of the early work was focused appropriately on discovery—fundamental research into methods of development and characterization of the properties of these materials. At present, these materials have not found widespread application, but the current focus of research in the field is more application-centered, as opposed to, material scale-up, system-level characterization of performance benefit, development of affordable materials, etc. Many proposed benefits of nanomet materials would be of interest to NAVAIR. Research performed suggests dramatic reductions in airframe and electronic system size, weight, and power are possible with nanomet materials.

In recognition of the potential of nanomet materials, NAVAIR convened a workshop with a set of subject matter experts to discuss the state-of-the-art and to identify focus areas for aircraft and weapons systems applications. The results of the workshop suggested significant benefits to command platforms in three areas: structures, energy and power, and antennas and metamaterials. The study discussed here is being performed to further define the specific benefits for NANOMETS for naval aircraft and to develop a strategy for enabling the command to certify and implement these innovative materials on future systems.

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BACKGROUND / PURPOSE

The objectives of the current study on nanomets are to identify technologies that could provide significant, game-changing capabilities for naval aircraft and weapons systems applications and to define the actions required by the command to implement systems that these materials enable. A preliminary assessment of nanomet research performed through an extensive literature review identified many interesting and relevant technologies. The study reported on here builds on this information to further explore applications in three important system areas: power and energy, structures, and antennas and metamaterials. Figure 1 illustrates a taxonomy relating relevant NAVAIR system areas and nanomet technologies that could provide a benefit. Figure 2 shows potential component level systems and applicability to aircraft. In the current study, the approach has been to attempt to quantify system performance benefits using NAVAIR-led working groups of subject matter experts. The working groups focused on identification of specific nanomet technologies, quantification of the system-level benefit, and identification of the S&T gaps that need to be addressed to allow implementation. A second, but equally important task for the study team was the identification of the NAVAIR infrastructure, in people and facilities that would be required to support implementation of promising nanomet technologies. The article discusses the results and findings pertaining to the Energy and Power study group.

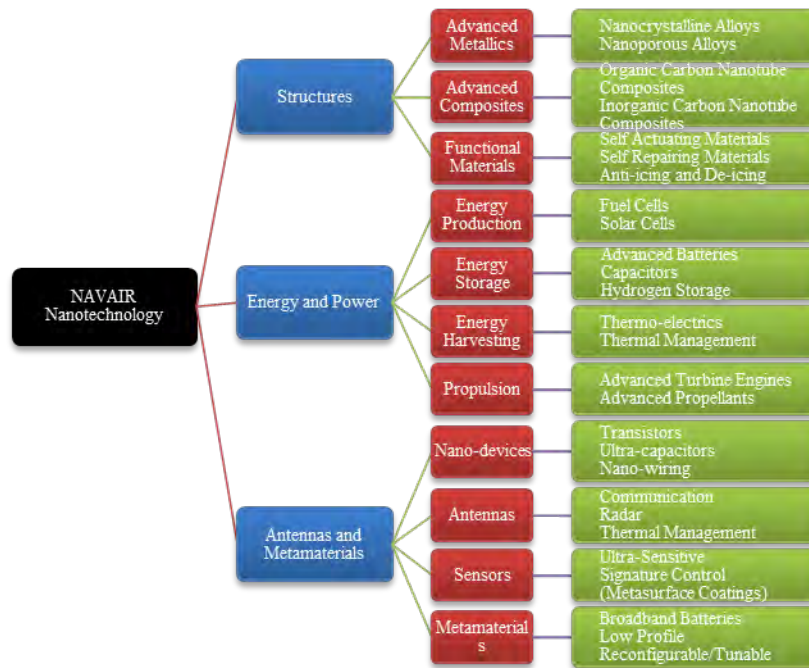


Figure 1: Relevant NANOMET Technologies to NAVAIR Systems and Platforms (1-22)

Nanomet Capabilities for Aircraft Systems

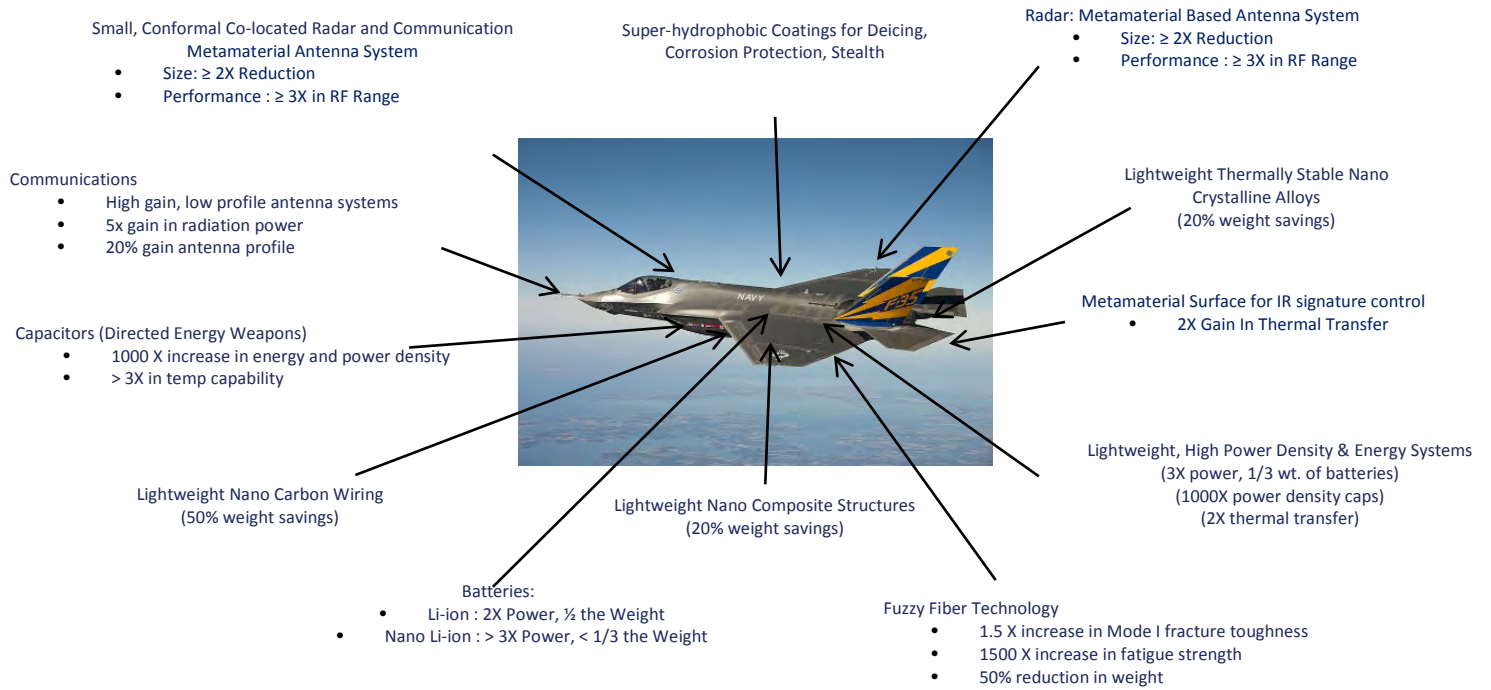


Figure 2: NANOMET Capabilities for Aircraft Systems and Unmanned Aerial Vehicles (UAVs)

DISCUSSION

BATTERIES

The Energy and Power Nanomet Study Group session on batteries discussed nano-enabling technologies and nano-materials that would impact the following platform systems: Directed Energy Weapons (DEW), Electric Driven Vehicles (EDV), aircraft batteries, and UAVs. Since nano-materials and nano-technologies cover such broad areas, various subcomponents highlighting each contribution were discussed by the study group. The battery session was further divided into anode, cathode, electrolyte, separator and emerging chemistries to discuss the nano-enabling benefits, challenges, US Navy benefit, application systems, and current technical readiness levels (TRLs) of each as listed in Table 1 in order to identify the benefit impact of each. However, there were several cross cutting themes related to all the categories related to the challenges and potential benefits. Nano-enabling technologies for the battery anode includes: using conductive additives (nano-wires and carbon nano-tubes [CNTs]), silicon-based active materials, developing 3-D structures and morphologies, realizing nano-based manufacturing techniques, identifying and developing new alloys and composite systems, CNT-based current collectors, and positive thermal coefficient of resistance safety materials. However, in order to realize the application system level benefits of these nano-enabling technologies, several challenges/gaps must be addressed which include: identifying methods to reduce material costs, reducing processing and manufacturing costs, addressing warfighter health safety concerns associated with nano-particles and nano-materials, identify methods for improving battery cycle life, develop scalable manufacturing processes to produce the necessary high volumes of reproducible nano-materials at affordable costs (i.e., low cost high rate manufacturing), and identify new advanced material systems. If these challenges/gaps could be addressed, then the Navy could realize a significant benefit from nano-enabling technologies that will affect systems performance such as providing higher power density, higher energy density (smaller systems), improved cycle performance (shorter battery recharge cycles), longer cycle life (longer missions), reduced weight, and improved safety. The current TRLs range from 2-4 for the current state of the art nano-enabling technology.

Other nano-enabling technologies for battery components include solid electrolytes, ionic liquids, and silicon-based electrolytes which would provide benefits in the form of improved safety (low flammability), higher operating voltages and higher energy densities, and improved reliability if the processes could be scaled for low-cost processing. Lastly, lithium-air and lithium-sulfur based batteries have the potential to significantly improve (orders of magnitude) energy densities over the current state of the art Li-ion battery provided improved catalysts can be identified, improved conductivity for sulfur addressed, and improved membranes developed.

In summary, addressing the technology challenges and gaps for battery system nano-enabling technologies will provide a significant benefit for the Navy for DEW, EDV, lightweight aircraft batteries, and UAVs.

Table 1: Battery Working Group Summary Highlighting Nano/Meta-Enabling Technology, Challenges, Benefits, and System Applications

Nano/Meta-Enabling Technologies (ANODE)	Challenges	Potential Benefit	Application Systems
1. Conductive additives (nano-wires, CNT)	1. Materials cost 2. Processing costs 3. Optimized volume fraction 4. Safety (EHS concerns nano-particulate) 5. CNT can accept Li ⁺ ions in its structure (even though used as conductive carbon) could lead to irreversible losses	1. Higher power density 2. Improved conduction path 3. Improved cycle performance by enhanced mechanical stability of particulate in “nano mesh/web”	DEW
1. Active materials (silicon based/anode only);	1. Cycle life (mechanical stability) 2. Materials cost	1. High capacity 2. Long cycle life 3. Improved safety	Electric driven vehicle
Morphologies (3-D structures, design concepts)	1. Scalable manufacturing 2. Processing costs 3. Conformal processing techniques	1. Higher power density 2. Improved conduction path 3. Higher rate capability 4. Higher aerial capacity	
Manufacturing methods	1. Traditional methods versus advanced techniques (feasibility) 2. Low cost high rate manufacturing	1. Cost (\$/kg) 2. High active materials loading and low dead weight 3. High energy density	
1. Alloys 2. Composites	1. Identifying novel materials 2. Volume expansion	1. Reduced weight 2. Long cycle life	Electric driven vehicle
CNT based current collector	1. Material cost; 2. Compatibility with existing manufacturing	1. Reduced weight/improved energy density; 2. High current capability	
Positive Thermal Coefficient of Resistance (PTCR) safety materials as an electrode layer	1. Production of materials (consistency) 2. Electrode processing	1. Automatic safety feature incorporated into electrode 2. Allows localized “shutdown” of only the hot spot on the electrode, not the entire cell 3. Potentially reversible effect	1. Aircraft batteries 2. UAV 3. DEW
Nano-enabling Technologies (CATHODE)	Challenges	Potential Benefit	Application systems
Conductive additives (nano-wires, CNT)	1. Materials cost 2. Processing costs 3. Optimized volume fraction 4. Safety (EHS concerns nano-particulate) 5. Impurities in CNT might produce shorts	1. Higher power density 2. Improved conduction path 3. Cycle life improvement 4. Reduced self-discharge	DEW
1. Active materials (silicon based/anode only); 2. Active materials coated on CNTs surface; 3. Active materials	1. Cycle life (mechanical stability) 2. Coating scale-up 3. Cost 4. Impurities in CNT can degrade performance 5. High packing density in electrodes	1. High capacity 2. Long cycle life 3. Improved safety	Electric driven vehicle

(nano-particle enabled multi-electron redox cathodes)			
Morphologies (3-D structures, design concepts)	1. Scalable manufacturing 2. Processing costs	1. Higher power density 2. Improved conduction path	
Manufacturing methods	1. Traditional methods versus advanced techniques (feasibility); 2. Low cost high rate manufacturing (scalability)	1. Cost (\$/kg)	
1. Alloys 2. Composites 3. High voltage, high capacity cathode materials (i.e., LiCoPO ₄ , LiNiPO ₄)	1. Identifying novel materials 2. Rate capability (requires nano-material)	1. Reduced weight 2. Higher powder density 3. Improved conduction path 4. High energy density	Electric driven vehicle
Positive Thermal Coefficient of Resistance (PTCR) safety materials as an electrode layer	1. Production of materials (consistency) 2. Electrode processing	1. Automatic safety feature incorporated into electrode 2. Allows localized “shutdown” of only the hot spot on the electrode, not the entire cell 3. Potentially reversible effect	1. Aircraft batteries 2. UAV 3. DEW
Nano-Enabling Technologies (Electrolyte)	Challenges	Potential Benefit	Application systems
Solid electrolytes	1. Scalability 2. Intrinsic properties (conductivity) 3. Pin hole free films 4. Uniformity	1. Improved safety (low flammability)	
Ionic liquids	1. Cost 2. Scalability 3. Conductivity for high power applications	1. High voltage (high energy density)	
Silicone-based electrolyte	1. Conductivity	1. Reliability 2. Safety 3. Higher voltage	
1. Potential alternative designs/systems (separator)	1. Increased allowable separator temperatures 2. Improved puncture resistance	1. Improved safety due to abuse 2. Mitigation of internal cell shorts	
Emerging Chemistries 1. Li-Air	1. Catalyst for redox reaction 2. Electrolytes 3. O ₂ -only permeable membrane	1. Orders of magnitude higher theoretical energy density than Li-ion	
2. Li-S	1. Polysulfide formation in electrolyte 2. Low conductivity of sulfur 3. Current low cyclability	1. Dramatically higher energy density than Li-ion	

CAPACITORS

The Energy and Power Nanomet Study Group session on capacitors (summarized in Table 2) discussed nano-enabling technologies and nano-materials that would impact platform systems such as DEW, aviation electronics, and UAVs. Electrostatic capacitors, electrochemical capacitors, and polymer film capacitors have the potential to provide higher energy density, higher power density, reduce weight, improve duty cycles (fast discharge and recharge rates for DEW and EMALS systems), and provide enough power for aircraft and ship weapon systems to meet mission requirements by reducing power supply size and weight (especially for aircraft directed energy weapon systems). Similar to the battery session, there were several cross cutting themes related to the challenges/gaps and potential benefits. The nano-enabling technologies include nano-composite dielectrics (ceramic/polymer composites), nano-laminates or nano-layered ceramic coated polymers, core shell materials, nano-based carbon such as CNT and graphene, coated nano-powders, higher temperature polymer systems and polymer coated glass systems. However, in order to realize these benefits, several technology challenges/gaps must first be addressed. For example, nano-layer ceramic coating thickness and material properties must be optimized to achieve good power density (i.e., dielectric constant and break down strength balance), processes must be scalable, systems that allow higher operating temperatures (>200C) with no reduction in performance need to be developed, more effective methods to disperse nano-particles for composite systems need to be developed to improve performance, better design and control of interfacial phenomenon for nano-layer or nano-composite systems are required, new methods to reduce failures due to voltage breakdown in polymer systems, reduced cost and volume, and scaling manufacturing processes need to be addressed. Current TRLs for the majority of the nano-enabling technologies for capacitors are TRL 2-4.

If these challenges could be addressed, then the Navy could realize a significant benefit from nano-enabling technologies that will affect system performance such as providing higher power density with better duty cycles for pulsed power applications, higher energy density (smaller systems), improved cycle performance, faster charging rates, reduced size, and reduced weight that would impact Navy DEW systems, EMALS, and aviation electronic systems.

Table 2: Capacitor Working Group Summary Highlighting Nano/Meta-Enabling Technology, Challenges, Benefits, and System Applications

	Nano/Meta-Enabling Technologies	Challenges	Potential Benefit	Application Systems
1.1 Electrostatic capacitors	1. Nano-composite dielectrics: barium titanate + polymer 2. Nano-laminates 3. Core shell materials	1. Optimization of properties to achieve good power density - dielectric constant and break down strength balance 2. Scalability and processability 3. Higher temperature performance (application dependent excess of 200C) 4. Nano-particle dispersion 5. Understanding discharge rate 6. Design and control of the interface	1. Increased mechanical properties, e.g., increased ductility 2. Increased energy density 3. Increased corona resistance 4. Reduced size and weight for devices, e.g., DEW and mission systems 5. Improved duty cycle (discharge and recharge).	1. DEW 2. Aviation electronics 3. EMALS
1.2 Electrochemical capacitors	1. Nano-carbons, e.g., CNT and graphene; 2. Coated nano-powders (inside and outside) 3. 3D structures, e.g., anodized aluminum	1. Cost - volume 2. Lowering the cost of electrode 3. Failures due to voltage break down in polymer systems 4. Electrochemical stability	1. Higher energy density (multiple times) 2. Higher power density 3. Heat loss 4. Weight savings	1. DEW 2. UAVs
1.3 Polymer Film Capacitors	1. Nano-composite dielectrics: various nonconducting ceramics, including core shell particles + polymers 2. Nano-copolymers and blends 3. High temperature polymers 4. Polymer coatings on glass 5. Polymer nano-laminates	1. Scalability to commercial volumes using cost effective methods is proving difficult 2. Higher temperature polymers are more difficult to process 3. Design of the interface between the nano-particles/phase is not well understood 4. Commercialization of these materials will depend on the cost value to the film manufacturers 5. Processable polymers for extrusion 6. Self-healing mechanism in high temperature polymers 7. Cost competitiveness with polypropylene	1. Increased thermal, mechanical, electrical properties 2. Increased energy density with better duty cycles for pulsed power 3. High ripple current applications for power electronics	1. DEW 2. Aviation electronics

FUEL CELL

The Energy and Power Nanomet Study Group session on fuel cells (summarized in Table 3) discussed nano-enabling technologies and nano-materials that would impact platform systems such as specialized UAVs, auxiliary processing units (APUs), and high efficiency battery recharging stations. The three primary nano-enabling technology areas discussed by the study group team were polymer exchange membrane (PEM) (also known as polymer electrolyte membrane) fuel cells, solid oxide fuel cell (SOFC), and fuel processors that would provide the Navy benefit with higher efficiency fuel cells, improved durability, higher voltage capability, higher power and energy density systems, reduced weight, shorter start up times, and longer continuous power capabilities for UAVs extended missions.

The nano-enabling technologies for fuel cell electrodes and electrolytes include nano-structured catalyst (films and particles) to provide high surface area, catalyst supports, identifying non precious metal (platinum) catalysts to reduce costs, developing nano-structured/scale coating for high temperature electrolyte/electrode interfaces to improve efficiency, improve high temperature electrolytes stability to improve fuel cell performance, identify improved anodes that can be used for regenerative hybrid fuel cell systems (i.e., solar power during the day and fuel cell at night), nano-crystalline ceramic oxide materials to control oxygen reduction reactions, development of nano-based coatings on bi-polar plates to reduce corrosion and maintain fuel cell efficiency, better hydrogen storage material systems, and liquid/gas sorbent materials. The primary challenges/gaps that must be addressed include improving the contamination tolerances that reduce FC efficiencies, improve catalyst dispersion to avoid clumping, improve higher temperature capability/stability, reduce manufacturing costs of complex active compounds, improve electrode stability in pure oxygen or liquid oxidants, reduce catalyst poisoning, improve material compatibility of fuel cell interconnects, improve high temperature stability, and reduce fuel cell costs.

If these challenges could be addressed, then the Navy could realize a significant benefit from nano-enabling technologies that will affect system performance such as providing higher efficiency fuel cells to reduce dependency on fossil fuels, improved component durability and reliability, higher power and energy density systems, reduced size and weight, shorter start up times, and longer UAV missions.

Table 3: Fuel Cell Working Group Summary Highlighting the Nano/Meta-Enabling Technology, Challenges, Benefits, and System Applications

	Nano/Meta-Enabling Technologies	Challenges	Potential Benefit	Application Systems
PEM FC				
Electrodes	1. Nano-structured catalysts (films and particles) and catalyst supports	1. Contaminant tolerance (both air/fuel); 2. Quality of coatings (dispersion); 3. Stability at high power density	1. Potential for higher efficiency 2. Reduced cost / PGM (platinum group metal) loadings	1. Specialized UAVs with H2 operation 2. APUs integrated with fuel processors for

				ground support and high-efficiency battery recharging.
	2. Non-precious metal catalysts	1. High manufacturing costs of complex non-PGM active compounds 2. Durability and contaminant resistance of non-PGM catalysts 3. Low activities of non-PGM catalysts (Navy is interested in electrodes stable in pure oxygen or liquid oxidants for the cathode and anodes that can be used for other fuels besides hydrogen (i.e. boron hydride))	1. Reduced cost / PGM loadings (reduced system size for fuel and oxidant for UAVs, UUVs, and portable power supplies for marines)	1. Specialized UAVs with H ₂ operation 2. APUs integrated with fuel processors for ground support and high-efficiency battery recharging.
Electrolytes	1. Nano-structured/scale coating for high-temperature electrolyte/electrode interfaces	1. Mitigating catalyst poisoning; 2. Improving durability of electrolyte/catalyst interface	1. Improved durability 2. Lower catalyst loadings; 3. High CO tolerance with more direct integration with hydrocarbon fuel processors 4. Higher operating voltage and thus higher efficiency stacks.	1. High-temp PEMFC systems for UAV power plants 2. High-temp PEMFC systems for APUs
	2. Improved high-temperature electrolytes	1. Immobilizing conducting species without requiring humidity	1. Improved durability 2. Improved high-temperature (> 100 deg. C, <200 deg. C) conductivity 3. High CO tolerance 4. More compact systems with smaller heat rejection	1. High-temp PEMFC systems for UAV power plants; 2. High-temp PEMFC systems for APUs
SOFC				
Electrodes	1. Nano-structured nano-material anode catalysts for direct heavy hydrocarbon utilization 2. Anodes that can be used for regenerative fuel cell systems (i.e.,	1. Logistic fuel contaminants 2. Coking/sintering; 3. High reforming activity 4. Contaminant tolerance (both air/fuel) 5. Durability 6. Ruggedness (regenerative fuel cells require anode that can be used for electrolysis of water without significant degradation)	1. Higher power and energy density systems 2. Higher efficiency 3. Logistics fuel tolerance 4. Continuous powering of UAVs or balloons for recon missions	1. UAV power plants operating on logistic fuels 2. Onboard APUs integrated with larger heat engines for large UAVs or other aircraft.

	solar power is used during the day for power and electrolysis of water to H ₂ and O ₂ , using fuel cell in reference, and then run fuel cell forward in the evening)			
	<ol style="list-style-type: none"> 1. Nano-crystalline oxide materials to support high rate thermal transient/transitions 2. Nano-catalyst enhancement of cathode for increased oxygen reduction reaction (ORR) kinetics - (cathode displays one of the highest resistance contribution for the fuel cell, researchers are impregnating ferrite and cobaltite nano-particulates into the pre-existing stable cathode to enhance the ORR kinetics) 	<ol style="list-style-type: none"> 1. Minimizing CTE mismatches 2. Reduced oxide-ion conductivities 3. Sintering and stability at high temperature 4. Microstructural stability of the nano-materials during operation (i.e. sintering/coarsening and reaction with cathode) 5. Impregnation of the needed amount for enhanced ORR may take many impregnation processes) 	<ol style="list-style-type: none"> 1. Reduced start-up times for high-efficiency fuel cells 2. Improved load following capabilities and therefore reduced weights for hybrid battery capacity. 	<ol style="list-style-type: none"> 1. UAV power plants operating on logistic fuels 2. Onboard APUs integrated with larger heat engines for large UAVs or other aircraft.
Electrolytes	<ol style="list-style-type: none"> 1. Nano-crystalline electrolytes for low-temp oxide conduction 	<ol style="list-style-type: none"> 1. Durability 2. Use of rare-earth materials 3. Processing limitations for nano-materials for large area cells, and defect and charge segregation at grain boundaries that eliminate potential enhancement 	<ol style="list-style-type: none"> 1. Faster start-up time 2. Improved durability 3. Reduced cost 	
Current Collection	<ol style="list-style-type: none"> 1. Nano-coatings on bi- 	<ol style="list-style-type: none"> 1. Metal diffusion/contamination of 	<ol style="list-style-type: none"> 1. Improved durability (reduced 	

	polar plates	electrodes	oxidation)	
Fuel Processors				
Catalysts	1. Nano-catalysts and additives used in wash-coats and binders; anchoring small diameter (high surface area), highly dispersed active catalyst nano-particles to the ceramic supports.	1. High temp stability 2. Cost 3. Tolerating fuel contaminants 4. Need microstructurally and chemically stable oxide or carbide nano-catalyst, and methods to synthesize these nano-materials [Many researchers can make them by bulk mixed-oxide, but can't make them at the nano-level]	1. Smaller footprint 2. Increased fuel conversion at higher space velocity 3. Lower PGM use 4. Durability 5. Fuel variation selectivity 6. More rapid start-up of liquid-fueled system	1. Compact logistic fuel reformers for UAV and APUs operating on liquid or logistic fuels at lower temperatures.
Sorbents	1. Nano-scale gas-phase sorbent materials	1. Sulfur-uptake capacity 2. Effective regeneration of sorbent 3. Stability of sorbent on support mechanism	1. Increased adsorption potential per unit volume 2. Reduced size and volume of sorbent component 3. Extended duration between maintenance action by end user	1. Smaller fuel processors for UAVs 2. Fuel cell APUs 3. Other logistic fueled fuel cell systems (both PEMFC and SOFC) 4. FC power generators 5. Lighter spark ignited IC engine operation on JP-8 6. Avoidance of wet stacking on tactical quiet generators
	2. Liquid phase sorbent potential use	1. Low selectivity and effectiveness of liquid-phase sorbents 2. Poor durability and regeneration capacity of liquid-phase sorbents	1. Ability to make sulfur free fuels from contaminated fuels in field 2. Higher power density for onboard fuel processors	1. Off board liquid-fuel cleanup for fuel cell systems and other logistic-fueled power plants 2. Efficient use of JP-8 (containing up to 3000 ppm sulfur) for Fuel Cell generators.

THERMAL MANAGEMENT

The Energy and Power Nanomet Study Group session on thermal management discussed nano-enabling technologies and nano-materials that would impact platforms involving high powered electronic devices, radar applications, other power electronic systems, next generation air vehicle skins, and low observable applications. The nano-enabling technologies, benefits, challenges, Navy benefit, application systems, and current TRLs for thermal management is listed in Table 4.

The nano-enabling technologies included advanced materials such as carbon-based electronics (diamond and graphene), nano-enabled heat pipes for cooling, vapor chambers, carbon nano-tubes, nano-structured thermal wicking materials, functionalized copper CNTs, silver filled epoxies, improved thermally conductive adhesives, nano-wires, nano-springs, nano-composites, nano-thermal interface materials and nano-layers, nano-enhanced heat fluids, phase change materials (PCM), nano-metamaterial technologies for directional heat flow, nano- and micro-channel scale features, micro/nano-textured fins to enhance convection and dissipate heat, identifying nano-composite materials comprised of low density and high conductive material systems, and novel thermoelectric materials. However, in order to realize the application system level benefits of these nano-enabling technologies, several challenges/gaps must be addressed such as improving thermal conductivity of the systems, improve heat flux and operating temperatures for both active and passive cooling architectures, improve integration/packaging methods for high powered devices, addressing system limitations caused by thermal expansion mismatch stresses, enhancing structural strength, improve reliability, chemical compatibility, and develop large scale nano-fabrication methods.

Addressing these gaps and challenges would result in improved “on chip” cooling which would result in improved power handling by a factor of three, which correlates to cheaper, more powerful electronic devices. Highly efficient heat spreading would enable increased power densities, increase operational temperatures, improved system performance (weight and power), and faster devices. Reducing interface thermal resistance on components would allow for better heat conduction/dissipation, increase long-term reliability and consistence from chip to chip, and reduce exotic heat spreading technology approaches to operate devices. Improved cold plate designs would provide higher heat dissipation capabilities for increased effectiveness of electronic components and directional heat dissipation, and uniform internal cooling of assembled components or systems (i.e., no hot spots). High efficiency heat exchangers would reduce power consumption in cooling systems, whereas tailored emitters would allow redistributed internal heat loads, increased thermal capacity, and radiate heat at acceptable wavelengths that are absorbed by atmosphere and therefore be undetectable at a distance. Lastly, thermoelectric conversion could permit effective, selective transfer of waste thermal energy from remote locations in lieu of conventional forced cooling methods resulting in overall system weight and power reductions. The current TRLs range from 2-5 for the current state of the art nano-enabling technologies capable of improving thermal management systems.

In summary, addressing the technology challenges and gaps for thermal management system nano-enabling technologies will provide a significant benefit to the Navy for system applications

involving high powered electronic devices, radar applications, and other power electronic systems.

Table 4: Thermal Management Working Group Summary Highlighting Nano/Meta-Enabling Technology, Challenges, Benefits, and System Applications

Nano/Meta-Enabling Technologies	Challenges	Potential Benefit	Application Systems
	Improve conductivity, heat flux and operating temperatures for both active and passive cooling architectures.		
1. Advanced materials (carbon-based electronics such as synthetic diamond), Graphene	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Improved ‘on chip’ cooling, Conductivity greater than current SiC components which results in improved power handling by a factor of three, resulting in cheaper, more powerful devices.	High powered electronic devices; radar applications, other power electronics
1. Chip-level forced liquid cooling (e.g. Near Junction Thermal Transport) 2. Nano-enabled heat pipes for cooling 3. Vapor chambers 4. Carbon Nano-Tubes (CNT) 5. Graphene (integrated spreaders) 6. Nano-structured thermal wicking materials for use in the Thermal ground plane, including copper-functionalized CNTs	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Highly efficient ‘heat spreading’ enable 1. Increased power density 2. Increased temperature capabilities 3. Thermal conductivities of >1000 W/mk Power savings 4. Large 2D area, <1mm thick, operation at 10g-20g 5. Structural, flexible, thin & light-weight materials 6. 2-phase heat transfer to eliminate load-driven thermal non-uniformity across substrate, Increased reliabilities 7. Heat reduction 8. Highly efficient heat spreading for high-power devices 9. Reduce operating temps by tens of degrees C. 10. Improved system performance (weight and power)	High powered electronic devices; radar applications, other power electronics
1. Graphene 2. Silver filled epoxy	1. Integration/packaging into high powered devices	Reduced interface thermal resistance 1. improve heat	High-powered

3. Thermally conductive adhesives 4. CNT 5. Nano-wires 6. Nano-springs 7. Nano-composites 8. Nano-thermal interface materials based on metallically bonded vertically aligned (VA) carbon nano-tubes (CNT) 9. Nano-structured layers	2. Coefficient of Thermal Expansion (CTE) matching 3. structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	conduction/dissipation 2. Increase Long-Term Reliability and Consistency from Chip to Chip 4. Three times improvement in RF output power 5. Reduce need for 'heat spreading' technology applications	electronic devices; radar applications, other power electronics
1. Nano-enhanced heat fluids 2. Phase change materials (PCM); Reversible PCM 3. Carbon nano-tubes	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. Structural strength; 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Improved cold plate designs with 1. on-axis thermal conductivities of greater than 3000 watts/meter kelvin (W/mK) 2. Increased effectiveness of electronic components and directional heat dissipation 3. Improved heat dissipation from electronics boxes	High powered electronic devices; radar applications, other power electronics
1. Nano/meta-material technologies for directional heat flow; controlled heat flow. 2. Photonic band gap 3. Topological insulators 4. Advanced heat transport technology including nano- and micro-channel scale features 5. Phase Change Materials	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. Structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Multi function enclosures with 1. Active/passive, non-uniform, tailorable heat dissipation, EMI shielding and grounding properties 2. Directional heat flow/insulation 3. Temperature dependent conduction 4. Increased strength/lower weight 5. Uniform internal cooling of assembled component or system	High powered electronic devices; radar applications, other power electronics
1. Micro/nano-textured fins to enhance convection surface area and turbulence 2. Nano-composite materials comprised of low density materials with high conductivity	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching; 3. Structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	High efficiency heat exchangers with 1. Reduced heat sink thermal resistance 2. Reduced air/fluid flow resistance through heat sink 3. Reduced power consumption in cooling systems	Thermal Management Systems
1. Textured	1. Integration/packaging into	Tailored emitters that allow	1. Next-gen

metamaterials (structures) to varying absorption & emission bands;	high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. Structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	1. Redistribute internal heat load 2. Increase thermal capacity 3. Radiate heat at acceptable wavelengths that are absorbed by atmosphere and therefore undetectable at a distance	air vehicle skins 2. Low observable applications
Novel thermoelectric materials	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. Structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Thermoelectric conversion could permit effective, selective transfer of waste thermal energy from remote locations in lieu of conventional forced cooling methods resulting in overall system weight and power reductions	High powered electronic devices; radar applications, other power electronics
	Improve conductivity, heat flux and operating temperatures for both active and passive cooling architectures.		
1. Advanced materials (carbon-based electronics such as synthetic diamond), Graphene	1. Integration/packaging into high powered devices 2. Coefficient of Thermal Expansion (CTE) matching 3. Structural strength 4. Reliability 5. Chemical compatibility 6. Large scale nano-fabrication methods	Improved 'on chip' cooling, Conductivity greater than current SiC components which results in improved power handling by a factor of three, resulting in cheaper, more powerful devices.	High powered electronic devices; radar applications, other power electronics

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CONCLUSIONS

The nanomet workshop has identified the following technology areas under the “Energy and Power” discipline that will benefit and significantly improve the capabilities for naval aircraft and weapons systems: lithium-ion batteries, capacitors, fuel cells, and thermal management.

One conclusion from the work accomplished to date is that the command should establish a Naval Aviation Center of Excellence (COE) to address this multidisciplinary cross-competency area. The COE should address important challenges for all of the potential systems applications, such as:

1. Multi-scale computational modeling capabilities
2. Scalable nano-manufacturing process capabilities
3. Quantification of performance/cost relationships

The existing community of interest (COI) comprising of various stakeholders within NAVAIR will be engaged further to identify the necessary infrastructure needed to implement the technologies. The plan is to interface the COI with academia, national labs, industry, and OEMs for standing up of COE.

The general consensus from these three groups is that there are tremendous benefits to be gained in platform performance through the use of these interesting new classes of materials.

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